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Ski Binding Suspension System for Vertical Load Transmission

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Ski Binding Suspension System for Vertical Load Transmission

A Major Qualifying Project Report submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science.

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ABSTRACT

The objective of this project is to use axiomatic design to design, prototype, and test a plate to absorb vertical loads to reduce anterior cruciate ligament (ACL), tibial plateau, and back injuries and avoid inadvertent heel release, by absorbing vertical loads and fore-aft torques while skiing. Conventional bindings do not protect against these three injuries, which can be expensive and keep people from skiing. One of the two main ACL injury mechanisms is the boot induced anterior drawer (BIAD), where an anterior shear load at the knee is produced by a forward torque transmitted from the tail of the ski, through a boot stiff in backward lean (Bere et al., 2011; Webster and Brown 1996). Tibial plateau injuries can be caused by vertical loads transmitted to the knee, resulting in fractures and bruising (Hunter, 1999; Johnson et al. 2008). To reduce the vertical loads, there is a plate supported by a controllable force suspension system. This system absorbs shocks and vibrations between the boot and the hard snow surface. It changes the natural frequency of the system to ease the dynamic loading on the back. Because there is essentially no vertical absorption in conventional bindings, this design can reduce some high frequency, short duration vertical loads on the skier by an order of magnitude. This allows for normal skiing technique under normal conditions and allows the skier to recover after the injury conditions have passed. Progressing with our initial design and concept, we intend on increasing the directions and axis of displacement with the goal of reducing other ACL skiing injury mechanisms.

Keywords: anterior cruciate ligament, axiomatic design, back injuries, constant force spring, ski, ski binding, sport-specific injuries, tibial plateau
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INTRODUCTION

1.1 Objective

Use axiomatic design to study and design a ski binding suspension system to avoid inadvertent heel release and reduce anterior cruciate ligament (ACL), tibial plateau, and back injuries by absorbing vertical loads and fore-aft torques while skiing.

1.2 Rationale

The current skiing injury rate is approximately 2 to 3 injuries per 1,000 skier-days (Koehle et al., 2002). A significant portion of these injuries include ACL tears. The ACL is affected in approximately 50% of all serious knee injuries and in about 20% of all skiing injuries (Ruedl et al., 2011). These injuries have become increasingly common as the boot height and stiffness has increased as shown in Figure 1 (Johnson et al., 1993).

![Figure 1: Mean Days Between Knee Injuries](image)

Current ski binding designs offer minimal absorption of the forces that are transferred during skiing. These bindings are adjusted using a linear spring and set to release at a certain force, allowing for minimal displacement of the binding. If a binding were able to displace twice
as much distance as it currently does, the forces transferred to the boot of the ski and subsequently the knee would be cut in half. The less force experienced at the knee would reduce injuries to the ACL as well as give the skier more time to recover. This drastic difference in loads while skiing would result in less injuries to the ACL.

ACL tears cause an extreme toll on the body and take many months of rehabilitation to fully recover. Not only does the body take a toll, but also the ACL reconstruction surgery is expensive. According to a 2017 study, there were 229,446 outpatient arthroscopic ACL reconstructions performed over the 9-year study period, the median immediate procedure cost was $9,399.49, and the median total health care utilization cost was $13,403.38 (Herzog et al., 2017). Preoperative rehabilitation for ACL surgery costed an average of $241, with postoperative rehabilitation costing $1,876 during a 6-month period (Zhang et al., 2015).

These injuries not only affect the skier but also the skiing industry. When a skier tears their ACL, they are not able to ski until they are fully healed which could be 6-9 months depending upon the rehabilitation and treatment process (van Grinsven et al., 2010). During this time the skiing industry is losing the injured person’s business in ski equipment and lift tickets. According to one study after 41.5 months 82% of participants had returned to some kind of sports participation, while only 63% returned to their pre-injury level of participation after tearing their ACL (Ardern et al., 2011). A system that is able to reduce ACL tears while maintaining the same level of performance and functionality of current ski bindings would benefit both the consumer and ski industry.

1.2.1 Mechanisms of an ACL Injury

The ACL is a ligament located in the knee, frequently torn due to high loads experienced during skiing (Jordan et al., 2017). Figure 2 shows the ACL in relationship to the kneecap, femur, and tibia. The ACL is intended to resist the combined translational and rotational motions of the tibia (Noyes, 2009). The two most common ways of injuring an ACL while skiing include boot induced anterior drawer (BIAD) and combined valgus, inward rotation (CVIR). These two mechanisms along with combined valgus, external rotation make up the three mechanisms for injuring the ACL while skiing (Maes et al., 2002).
Boot induced anterior drawer (BIAD) occurs when a skier loses their balance backwards while in the air. The skier then lands on the tail of their skis with their legs extended. As the skier lands, the loads are transferred through the skis, bindings, and stiff boots, resulting in an anterior drawer of the tibia relative to the femur as shown in Figure 3. The lack of flexibility in the back of the ski boot holds the tibia in place during impact while the center of mass of the skier continues to fall backwards, pulling the femur off of the tibia. This landing puts sufficient strain on the ACL, potentially causing injuries (Bere et al., 2011).

Combined valgus, inward rotation (CVIR) occurs when the skier’s body is facing downhill, their uphill arm is back, and their balance is backwards with no weight on the uphill ski. The skier’s hips are lower than their knees with their weight on the inside edge of the
downhill as shown in Figure 4. As the downhill ski engages with the snow, the inside edge at the tail engages, rotating the downhill knee inwards. This rotation causes the ACL to unnaturally twist, potentially causing the ACL to tear (Bere et al., 2011).

![Figure 4: CVIR Injury Mechanism - Lateral Motion (Radiology Key, 2016)](image)

In addition to ACL injuries, tibial plateau injuries and spinal bruising are common in high level skiing. These fractures or bruising result from the forces of skiing being transmitted to the knee from the hard snow surface. This high energy injury involves the lateral plateau and the anterior half of the joint in compression (Hunter, 1999).

1.3 State of the Art

Typical ski binding systems are designed to have a single pivot point to allow rotation about the boot heel, making the binding-release system ignore applied loads located at or near the heel. New binding systems have tried to change the point of rotation by either shifting the location or adding a second pivot point.

1.3.1 KneeBinding

The KneeBinding as shown in Figure 5, is an American made ski binding that has two pivot points: rotation about the boot heel that releases at the toe and rotation about the boot toe that releases at the heel (Springer, 2016). This design ultimately eliminates the dead zone of a typical ski-binding system, which is the area of the ski that does not transmit applied forces to the binding resulting in horizontal release from the binding.
1.3.2 Reactor 12 by Line Skies – Features Pivogy

Similarly, Line Skis binding product the Pivogy shown in Figure 6, is designed with a dual pivot point system. By shifting the pivot point, the design is able to reduce the torque on the knee by a factor of three relative to existing single-pivot bindings (Simmon, 2003).

1.3.3 Tyrolia Diagonal Toe and Heel Binding

The Tyrolia Full Diagonal Toe Binding is able to release at the toe a full 180° when there is a torque greater than the predetermined release torque. The Diagonal Heel portion of the binding is able to release at 150° of motion with 90° being vertically up and ranging ±15° shown in Figure 7. Despite these revolutionary designs, the bindings have had very little success on the market due to problems within the industry, manufacturing, and investors (Tyrolia, 2019).
1.3.4 Dodge Boot

The Dodge Boot as shown in Figure 8, is a ski boot made from carbon fiber and has a liner meant to absorb high frequency, low amplitude vibrations, which changes the natural frequency of the system. This absorption system is meant to protect from tibial plateau and back injuries (Dodge Ski Boot, 2019).

1.3.5 Past Major Qualifying Projects

In past Major Qualifying Projects (MQPs) at Worcester Polytechnic Institute (WPI), many groups have engineered potential solutions of ski binding designs to prevent ACL injuries by absorbing injurious loads through the displacement of some mechanism(s). This displacement
must be instantaneous to prevent inadvertent release and allow the skier to regain control as quickly as possible.

1.3.5.1 Design of ACL Absorption Plate (2007)

This project aimed to absorb injurious loads by displacing the heel about the pivot point located at the ball of the foot. Unlike developed products, this design consists of two plates: a top plate that is attached to the binding and a bottom plate that is attached to the ski as shown in Figure 9. As a result of the vertical displacement of the plates, some of the applied force is absorbed and the skier is affected by a lower force.

![Figure 9: Design of ACL Absorption Plate](image)

1.3.5.2 Advanced Design of a Binding Plate to Reduce Anterior Cruciate Ligament Injury (2013)

This group used a single plate design that could displace vertically upward at the toe and vertically downward at the heel. This design has specifically minimized the plate-ski height to comply with the International Ski Federation standards for combined plate, ski, and binding height as shown in Figure 10. This design is unique in the fact that the rotational motion is converted to linear motion through a linkage system. When the plate undergoes displacement, thus resulting in rotation, the link transmits the displacement to a vertically standing bolt in the heel component of the binding, which in turn displaces the spring.

![Figure 10: Advanced Design of Binding Plate to Reduce ACL Injury](image)
1.3.5.3 Design of Binding Plate to Provide High Performance, Injury Free Skiing (2014)

This design incorporates two interlocking plates that further reduce the plate-ski height compared to the 2007 project. The plates laterally displace about the pivot point at the toe and the injurious forces are absorbed by a cantilever spring in between the plates as shown in Figure 11.

![Design of Binding Plate](image)

*Figure 11: Design of Binding Plate to Provide High Performance, Injury Free Skiing*

1.4 Absorption Mechanisms

There are many ways to absorb a force by displacement. One technique is a compression spring, which displaces at a direct linear rate when a force is applied as shown in Figure 12. These springs can be adjusted to a preloaded position to engage at a specific force. Engagement with a constant force spring begins with a brief linear displacement until a predetermined load is reached. It continues to displace under that load, until the load is released or decreased below the predetermined threshold. This can be seen in Graph 1, where the force stays constant as the spring continues to displace. The challenge associated with a constant force spring is that the force at which it displaces is difficult to adjust.
Current bindings have almost no displacement, so when a skier lands, or begins to fall, the maneuver creates a large vertical force. If this force is large enough and directed upward at the heel, the heel release mechanism in the binding actuates, releasing the skier from the ski. This system does not allow the skier to recover as the release from the binding is instantaneous. Additionally, because the toe releases laterally, a vertical force above the injury threshold, will release the skier at the heel, but can still cause injury as the toe cannot lift. To reduce the peak vertical force, an absorption plate was developed to displace when a large force is generated by the skier. This plate will keep the skier below injury loads using a constant force spring to give them time to recover.

The Goat Head Spring, patented by Professor Brown, is a constant force spring that follows the natural shape of the horns of a goat, thus explaining the name as shown in Figure 12. Unlike normal linear springs, the Goat Head Spring is expected to displace very quickly and continue displacing at a constant force. Upon unloading of the applied force, the Goat Head Spring will return to its original shape following hysteresis of the force vs. displacement curve.
1.5 Approach

1.5.1 Advancing the State of the Art

This project worked to advance the state of the art by developing a system to absorb vertical loads at both the heel and toe of the boot. Allowing both the heel and toe of the boot to displace in the positive and negative vertical directions accommodates multiple scenarios where a skier could be injured.

In prior state of the art, there are binding designs which focus solely on releasing the boot from the binding when the skier produces a load capable of tearing their ACL. This project worked to absorb loads above ordinary skiing loads in order to allow the skier to recover and continue skiing rather than immediately releasing from their bindings.

In other previous state of the art solutions absorption systems were used, however none used a constant force spring system. A constant force spring system provides the skier with maximum time to recover from loads greater than that of normal skiing and remains rigid under ordinary skiing loads.

1.5.2 Axiomatic Design

Axiomatic design is a structured design method that has two axioms. Axiom 1, the Independence Axiom, states to maintain the independence of the elements of the design. Axiom 2, the Information Axiom, minimizes the information required of the functions. Axiomatic design has the designer consider the customer’s needs (CNs) throughout the entire process to determine what is needed for the design to hold value and determines the functional requirements (FRs). Selecting design parameters (DPs) that correspond with the FRs develop a physical solution for the customer. To further the detail of the design, levels of FRs and DPs are created until every aspect is defined in the design and the solution is obvious. To maintain the independence of the functional requirements, each requirement must have a different design parameter so there is no DP performing multiple functions resulting in coupling. A ‘good’ design is collectively exhaustive and mutually exclusive (CEME) meaning each element of the design performs one function and all aspects of the customer’s needs have been satisfied (Suh, 2001).

Part of the axiomatic design process is to improve upon past design solutions to generate a design that follows the two axioms. Throughout the process, multiple iterations were completed to improve simplicity of design by redefining customer needs and identifying design constraints. The final axiomatic decomposition of the Suspension System shown in Figure 13...
was built in Acclaro, an organizational software for axiomatic design. For initial and midpoint iterations see Appendix A.

Figure 13: Final Axiomatic Decomposition of Ski Binding Suspension System
DESIGN CONSTRAINTS AND DECOMPOSITION

2.1 Design Constraints

Many constraints were considered to produce a final product design that is not only effective but satisfies the customers’ needs. These constraints include:

1. Size of plate system
2. Weight of plate system
3. Manufacturing costs
4. Retail costs
5. Project budget
6. Environmental conditions
7. Compatibility with skiing equipment
8. Versatility for various skier’s ability, alpine skiing style, age, and weight
9. Control and safety of skier
10. Limited data on injurious skiing loads

Design specifications were chosen based on the demands of the average female, downhill alpine race skier. A design that satisfies these highest-level design constraints can accommodate for any skiing ability and style. The size of the plate system must comply with the Alpine Equipment Regulations of the 2017-2018 ski season for age groups US19 and older. A complete list of regulations can be found in Appendix B.

Additionally, the weight of the plate system must be limited to reduce ground reaction forces and maintain the maneuverability of the skiing equipment. The costs to manufacture and sell the plate system must be comparable to that of other skiing equipment (skis, boots, bindings, helmet, etc.). All materials purchased for the production of a prototype must be within the project’s budget of $1000 ($250/student) as outlined by WPI’s Mechanical Engineering department. Materials must be able to withstand dramatic changes in temperatures and be protected against jamming caused by snow conditions.

The plate system must attach to the ski without interfering with the structure and function of the ski, in addition to the placement and function of the ski binding. The plate system must properly function for any range of skiing ability from beginner to expert. This design followed the constraints of downhill alpine skiing. In the future, the design can be modified for other skiing styles including ski jumping, freestyle, and slalom skiing. When using the plate system,
the skier must be able to maintain control of proper skiing technique and form. Different types of skiing can produce various changes in loads.

Limited data about injurious loads is available due to unethical means of extruding measurements and any study considered may be bias. It is important that all these constraints are considered in order to reduce further risk of unintended injuries. A complete list of design constraints is found in Table 1 and a complete list of selection criteria is found in Table 2.

Table 1: Design Constraints

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Justification</th>
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| Width of plate must be less than the max standard: Downhill - 95 mm | Alpine Equipment Regulations 2017-2018 (US19 and Older) 
Ski profile width under FIS 
*National has no rule |
| Standing Height (ski/plate/binding) must be less than 50 mm | Alpine Equipment Regulations 2017-2018 (US19 and Older) 
Standing Height for all events (women and men) |
| Boot height (from sole of boot to top of foot bed) must be less than 43 mm | Alpine Equipment Regulations 2017-2018 (US19 and Older) 
Boot Height for all events (women and men) |
| Withstand Vertical Critical Load ($F_{VC}$) of 2.25*Body Weight | (Nakazato, Scheiber & Müller, 2011) |
| Boot Interface | ISO 5355 Alpine ski boots- Requirements and test methods |

Table 2: Selection Criteria

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Justification</th>
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<tbody>
<tr>
<td>Deflection at Injurious Loads</td>
<td>Control the suspension system by replicating the force vs. displacement curve</td>
</tr>
<tr>
<td>Heel Height</td>
<td>Must comply with design constraints to minimize risk of injury</td>
</tr>
<tr>
<td>Toe Height</td>
<td>Must comply with design constraints to minimize risk of injury</td>
</tr>
<tr>
<td><strong>System Mass</strong></td>
<td>Must minimize weight to increase athletic performance</td>
</tr>
<tr>
<td>-----------------</td>
<td>------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Cycles to Failure</strong></td>
<td>Shoes are designed to endure thousands of steps, which in this case would be thousands of load cycles (Caselli, 2006)</td>
</tr>
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### 2.2 Decomposition

This section will focus on elaborating on the functional requirements and design parameters of the axiomatic decomposition.

**FR0: Transmit loads to protect the knee and back from injury while skiing**
The first functional requirement, FR0, is based off the customer’s need for injury free skiing. The following FRs are children of FR0 and can be further decomposed until deemed collectively exhaustive and mutually exclusive (CEME). The most important part of skiing is transmitting loads therefore, this decomposition focuses on transmitting ordinary loads and absorbing any load greater than ordinary to protect the skier from injury.

**DP0: Spring and lever absorption system**
For proper load transmission between the skier and ski, a spring and lever system modification will be used with the purpose of vertically displacing the skier at the toe and heel.

**FR1: Transmit loads from binding to top plate**
It is important to be able to transmit loads from the ski bindings to the top plate. The loads that a skier is applying to the ski boot are transferred to the typical bindings, mounted on a plate. This allows the individual to use normal bindings with the absorption system.

**DP1: Screws to connect bindings to top plate**
To fulfill the requirement of FR1, bindings are fixed to the top plate using standard binding screws that thread into tapped holes, following the required binding hole pattern on the top plate.

**FR2: Transmit loads from top plate to lever system**
The loads must then be transmitted from the top plate into a lever system. This lever system will vary the forces further transmitted allowing for adjustability and stability with roll and yaw moments.

**DP2: Pin and slot system at toe and heel**
A pin and slot method is used to transmit loads from the top plate to the lever system. The lever is slotted while the top plate will have a through hole. A pin is inserted to allow the system to transfer loads across the top plate to the levers. Without the slot the system would be rigid and unable to displace vertically.

**FR3: Transmit moments through lever system**
Once the loads have been transmitted to the lever system, the moments must be transmitted through the lever system. This provides a stable platform for the skier to use to turn while skiing.
DP3: Pin and fulcrum supports at toe and heel
A fulcrum located between the effort and load is required to transmit loads through the class 1 lever. A pin through the lever engages with a set of fulcrums located at the toe and heel, allowing moments through the lever.

FR4: Transmit loads from base plate to the ski
The loads of a skier must then be transmitted from the base plate into the ski to allow the ski to flex and the skier to ski normally.

DP4: Fasteners from base plate into ski (at binding mounting holes)
The transmission of loads from the base plate to the ski is accomplished by using standard binding mounting hole patterns on the ski and fastening the base plate by use of screws.

FR5: Transmit loads from lever system to springs
The loads transmitted through the lever system are then transmitted into springs to displace above ordinary loads.

DP5: Actuator
An actuator is used to apply a load to the spring system from the lever. The actuator consists of a pin constrained by the end of the lever, with radii identical to the inner radius of the springs for maximum engagement.

FR6: Transmit loads from springs to ski at the heel
The loads transmitted to the springs must then be transmitted into the ski at the heel of the binding system. To transmit the loads from the springs into the ski, FR6 is decomposed into 5 additional children.

DP6: Fasteners from spring housing to base plate at the heel
The spring housing containing the springs at the heel are fixed to the base plate to transmit loads from the spring system to the ski using fasteners.

FR6.1: Transmit ordinary loads at the heel
Typical loads experienced during skiing must be transmitted through the system to maintain normal skiing techniques.

DP6.1: Stationary boot and binding
To transmit ordinary loads at the heel, the boot and binding are static during ordinary loads, similar to a typical boot and binding system.

FR6.1.1: Transmit pitch moments
Pitch moments, or forward and backward loads on the ski are transmitted through the spring system into the ski.

DP6.1.1: Static controllable force spring system
To transmit pitch moments at the heel, the force spring system is entirely static under ordinary loads.

**FR6.1.2: Transmit yaw moments**
Yaw moments are side to side forces on the system. These moments promote inadvertent release in a typical binding system.

**DP6.1.2: Fulcrum supports fastened to base plate**
To transmit yaw moments at the heel, the fulcrum supports are fastened to the base plate, preventing relative rotation between skier and ski in the yaw directions.

**FR6.1.3: Transmit roll moments**
Roll moments transmitted through the system are small vertical loads on either side of the system. Transmitting these loads allows a skier to engage the ski’s edges while turning.

**DP6.1.3: Fulcrum supports fastened to base plate**
To transmit roll moments at the heel, the fulcrum supports are fastened to the base plate, preventing rotation in the roll directions.

**FR6.2: Displace vertically above ordinary loads**
To protect a skier from vertical loads, the springs must displace above ordinary skiing loads.

**DP6.2: Dynamic controllable force spring system**
The spring system becomes dynamic to displace vertically when greater than ordinary loads are applied.

**FR6.2.1: Displace top plate vertically in positive direction**
The springs displace in a negative direction to allow the heel to displace in a positive direction, up and away from the base plate.

**DP6.2.1: Spring below the actuator**
A spring is located below the actuator to displace the top plate in the positive vertical direction.

**FR6.2.2: Displace top plate vertically in negative direction**
The springs displace in a positive direction to allow the heel to displace in a negative direction, down towards the base plate.

**DP6.2.2: Spring above the actuator**
A spring is located above the actuator to displace the top plate in the negative vertical direction.
FR6.3: Control vertical displacement
The force required for the system to displace above ordinary loads must be controlled to prevent injury.

DP6.3: Spring stiffness
Spring stiffness selection, which can be altered by change in spring material, thickness, width, and/or radius, allows control of maximum required load prior to vertical displacement.

FR6.4: Transmit loads while ski is flexed
To maintain normal skiing, the ski must be able to flex under a load as it would without an additional plate system.

DP6.4: Clearance in pin system
Clearance in the pin and slot system, which connect the top plate to the lever system, allows the ski to flex normally.

FR6.5: Transmit loads for variety of skiers
To market the system to the general skiing population, as well as the elite athletes, the system must be adjustable for different skiers.

DP6.5: Controllable force spring system adjustments
The system can be adjusted for a variety of skiers based on their height, weight, boot size, and skiing expertise, which alters the applied force needed to displace the top plate.

FR6.5.1: Make course adjustments
The system must make large adjustments for major differences in height and weight of skiers and their abilities.

DP6.5.1: Replaceable spring (change spring stiffness)
For a coarse adjustment, the springs can be replaced with springs of the same radius but variance in material and mechanical properties, by removing the spring support and exchanging the springs.

FR6.5.2: Make fine adjustments
The system must make small adjustments for minor differences in height and weight of skiers and their abilities.

DP6.5.2: Change fulcrum point of lever system
For fine adjustment, the fulcrum point can be translated with the use of numerous fulcrum mounting hole options on the base plate and multiple pin-hole locations on the lever. This changes the ratio between effort/fulcrum and load/fulcrum.

FR7: Transmit loads from spring to ski at the toe
Similar to FR6, the loads transmitted to the springs must then be transmitted into the ski at the heel of the binding system. To transmit the loads from the springs into the ski, FR7 is decomposed into 5 additional children.

**DP7: Fasteners from spring housing to base plate at the toe**
The spring housing containing the springs at the heel are fixed to the base plate to transmit loads from the spring system to the ski using fasteners.

**FR7.1: Transmit ordinary loads at the toe**
Typical loads experienced during skiing must be transmitted through the system to maintain normal skiing techniques.

**DP7.1: Stationary boot and binding**
To transmit ordinary loads at the toe, the boot and binding are static during ordinary loads, similar to a typical boot and binding system.

**FR7.1.1: Transmit pitch moments**
Pitch moments, or forward and backward loads on the ski are transmitted through the spring system into the ski.

**DP7.1.1: Static controllable force spring system**
To transmit pitch moments at the heel, the force spring system is entirely static under ordinary loads.

**FR7.1.2: Transmit yaw moments**
Yaw moments are side to side forces on the system. These moments promote inadvertent release in a typical binding system.

**DP7.1.2: Fulcrum supports fastened to base plate**
To transmit yaw moments at the toe, the fulcrum supports are fastened to the base plate preventing relative rotation between skier and ski in the yaw directions.

**FR7.1.3: Transmit roll moments**
Roll moments transmitted through the system are small vertical loads on either side of the system. Transmitting these loads allows a skier to engage the ski’s edges while turning.

**DP7.1.3: Fulcrum supports fastened to base plate**
To transmit roll moments at the toe, the fulcrum supports are fastened to the base plate preventing relative rotation between skier and ski in the roll directions.

**FR7.2: Displace vertically above ordinary loads**
To protect a skier from vertical loads, the springs must displace above ordinary skiing loads.

**DP7.2: Dynamic controllable force spring system**
The spring system becomes dynamic to displace vertically when loads greater than ordinary loads are applied

**FR7.2.1: Displace top plate vertically in positive direction**
The springs displace in a negative direction to allow the toe to displace in a positive direction, up and away from the base plate.

**DP7.2.1: Spring below the actuator**
A spring is located below the actuator to displace the top plate in the positive direction.

**FR7.2.2: Displace top plate vertically in negative direction**
The springs displace in a positive direction to allow the toe to displace in a negative direction, down towards the base plate.

**DP7.2.2: Spring above the actuator**
A spring is located above the actuator to displace the top plate in the negative direction.

**FR7.3: Control vertical displacement**
The force required for the system to displace above ordinary loads must be controlled to prevent injury.

**DP7.3: Spring stiffness**
Spring stiffness selection, which can be altered by change in spring material, thickness, width, and/or radius, allows control of maximum required load prior to vertical displacement.

**FR7.4: Transmit loads while ski is flexed**
To maintain normal skiing, the ski must be able to flex under a load as it would without an additional plate system.

**DP7.4: Clearance in pin system**
Clearance in the pin and slot system, which connect the top plate to the lever system, allows the ski to flex normally.

**FR7.5: Transmit loads for variety of skiers**
To market the system to the general skiing population, as well as the elite athletes, the system must be adjustable for different skiers.

**DP7.5: Controllable force spring system adjustments**
The system can be adjusted for a variety of skiers based on their height, weight, boot size, and skiing expertise, which alters the applied force needed to displace the top plate.

**FR7.5.1: Make course adjustments**
The system must make large adjustments for major differences in height and weight of skiers and their abilities.

**DP7.5.1: Replaceable spring (change spring stiffness)**
For a coarse adjustment, the springs can be replaced with springs of the same radius but variance in material and mechanical properties, by removing the spring support and exchanging the springs.

**FR7.5.2: Make fine adjustments**
The system must make small adjustments for minor differences in height and weight of skiers and their abilities.

**DP7.5.2: Change fulcrum point of lever system**
For fine adjustment, the fulcrum point can be translated with the use of multiple fulcrum mounting holes on the base plate and multiple pin holes on the lever. This will change the ratio between the effort/fulcrum, and load/fulcrum.

**PHYSICAL INTEGRATION**

---

**3.1 Suspension System Design**

Based on the customer needs and corresponding functional requirements of the design, design parameters were chosen that best met the functional requirements. The culmination of those design parameters resulted in the suspension system design shown in Figure 14.

![Figure 14: Exploded Model with Design Parameters](image-url)
All types of ski bindings are able to attach to the top plate, and the bottom plates attach directly to the ski. The lever arms interface with the top plate by a pin and slot system and connect with the actuator and spring system with a pin. The stiff boot and binding that is attached to the skier is able to move relative to the ski when forces approach injurious loads. This displacement causes a decrease in forces applied to the knee and allows the skier additional time to recover and prevent injury. However, during normal skiing loads the constant force spring maintains a rigid system so normal skiing performance is preserved. The Goat Head Spring was chosen for the controllable spring system. The unique loading and unloading pattern of the spring allows the skier to recover from injurious loads instantaneously without experiencing forces within the muscular and skeletal structure that result in injuries.

3.2 Design Matrix

A mathematical representation of axiom 1 can be represented using the following equation and is represented in Figure 15 (Shetty, 2015).

\[
[FR] = [DM][DP]
\]

Where:

- \([FR]\) = vector of function requirement
- \([DP]\) = vector of design parameters
- \([DM]\) = relationship matrix between functional and physical domain

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3 \\
.. \\
FR_n
\end{bmatrix} = \begin{bmatrix}
X & 0 & 0 & .. & 0 \\
0 & X & 0 & .. & 0 \\
0 & 0 & 0 & .. & 0 \\
.. \\
0 & 0 & 0 & X
\end{bmatrix} \begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3 \\
.. \\
DP_n
\end{bmatrix}
\]

**Figure 15: Design Matrix**

There are three types of design equations used to describe the FR and DP relationship: uncoupled, decoupled, and coupled. The matrix \([DM]\) should be either triangular or diagonal to
satisfy axiom 1. Both an uncoupled (diagonal) and decoupled (triangular) design matrix satisfy the independence axiom.

The ideal design matrix indicates an uncoupled design, which means that each functional requirement has a single corresponding design parameter shown in Figure 16. An element of \([DM]\), \(X_{ij}\) represents the relationship between each \(FR_i\) and \(DP_j\). If \(FR_i\) is affected by \(DP_j\), then \(X_{ij}\) has a finite value and is indicated with a blue colored box and an “X”. If \(FR_i\) is not affected by \(DP_j\), then \(X_{ij}\) has a value equal to zero and is indicated with a green colored box and an “O”.

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix} =
\begin{bmatrix}
a_{11} & 0 & 0 \\
0 & a_{22} & 0 \\
0 & 0 & a_{33}
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\]

*Figure 16: Uncoupled Design Matrix*

The design is decoupled when the matrix is triangular. For example, \(X_{nm} = 0\) when \(n \neq m\) and \(m > n\) as shown in Figure 17. If the matrix does not satisfy axiom 1, then it is a coupled design as shown in Figure 18.

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix} =
\begin{bmatrix}
a_{11} & 0 & 0 \\
a_{21} & a_{22} & 0 \\
a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\]

*Figure 17: Decoupled Design Matrix*
A design matrix was created for this project to check for the relationships between the FRs and DPs and minimize coupling throughout the design as shown in Figures 19 and 20. A matrix that satisfies axiom 1 maximizes the probability of fulfilling successful FRs, thus leading to a successful design solution.
There are aspects of this design decomposition that can be improved upon to remove coupling within the design. The coupling is partially a result of the constraints of the design that limit the available space for the Suspension System.

3.3 Material Selection

3.3.1 Demonstration Prototype

The top plate, lever arms, base plate, fulcrum supports, and spring frame walls of the demo prototype are made up of clear acrylic. The manufacturing process is simplified through the use of laser cutting, a relatively quick process that requires minimal set up, operating time, and cleanup processes. Due to the material’s transparency, clear acrylic can effectively showcase mechanisms of the complete absorption system. The strength and mechanical properties of acrylic are sufficient for the forces being applied to the demo model. The pins are made from 6061 Aluminum, a relatively inexpensive, easily machinable, and lightweight metal with satisfactory mechanical properties. The coefficient of friction between aluminum and acrylic has an acceptable $\mu$ value of 0.20 (Bowden, Tabor, 1951).

3.3.2 Springs

Material for the constant force Goat Head Spring was selected using strain calculations based on the geometry of the spring. These strain calculations were used along with material properties and varying dimensions of the spring to get an acceptable force at which the spring will begin to strain. An applied force ranging from 66.72 to 88.96N (15 to 20lbs) was determined to be sufficient for the demo to easily displace for interactive demonstrations with minimal exertion. Teflon yielded acceptable force calculations based on the dimensions chosen. It was machined on a CNC mini mill by gluing a sheet of the Teflon to a piece of aluminum stock.
3.4 Finite Element Analysis

Finite element analysis (FEA) was utilized in Solidworks to obtain stress, strain, and displacement results of various absorption system parts. Static analysis was performed on the top plate and lever arms. Force values applied were determined from a study found in literature measuring the max force measured while skiing. The maximum force measured was 2.25 times body weight. For safety reasons 2.5 times body weight was used for the top plate and lever arm FEA’s, which can be seen in Figures 21 and 22. Calculations were based on a force of 2800 N (629.465lbs) to simulate a person of 1112.5N (250lbs). From this analysis 6061 T-4 Aluminum was determined to have acceptable mechanical properties as it would not plastically deform under the forces applied to it.

Figure 21: Top Plate Stress FEA
Static analysis was also performed on the fulcrum supports to ensure each could withstand the forces during transmission of roll moments. The following equation was used to calculate the forces used in the analysis:

\[ F_c = \frac{(mv^2)}{r} \]

Where:
- \( F_c \) = Centripetal force (N)
- \( m \) = mass of the skier (kg)
- \( v \) = velocity of skier (m/s)
- \( r \) = radius of turn the skier makes (m)

The values chosen for simulation of FEA are aggressive to yield a high force value and maximize the safety factor of the design as shown in Table 3. Not only were the calculations aggressive, but the forces were only applied to one edge of the system as well to ensure that the parts and materials chosen would be able to withstand the forces in the least advantageous situation. These force values were applied both up and down axially on the fulcrums, where the force would be applied by the pin connecting the supports to the lever. These FEA’s are shown in Figures 23 and 24.
### Table 3: Simulation Values for FEA Analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight ($F_{\text{weight}}$)</td>
<td>1112.5N (250lbs)</td>
</tr>
<tr>
<td>Velocity (v)</td>
<td>35 m/s</td>
</tr>
<tr>
<td>Radius (r)</td>
<td>5 m</td>
</tr>
</tbody>
</table>

Calculations for Centripetal Force:

\[
F_{\text{weight}} = m \times g
\]

\[
m = \frac{1112.5N}{9.81m/s^2} = 113.4 \text{ kg}
\]

\[
F_c = \frac{(113.4kg \times (35m/s)^2)}{5m} = 27,783N
\]

Figure 23: Fulcrum Support - Force Applied Down Stress FEA
An additional analysis was also performed on the fulcrum supports to ensure they would withstand forces transmitted by yaw moments. The following equation was used to determine the maximum forces needed to be transmitted and used in the FEA:

\[ F_t = m \times g \times \cos(\alpha) \]

Where:
- \( F_t \) = Tangential force
- \( m \) = mass of the skier
- \( g \) = acceleration due to gravity
- \( \alpha \) = lean angle

The values chosen for this FEA, depicted in Table 4 were also aggressive to yield higher force values to maximize the safety factor. To ensure safety, the situation chosen was the least advantageous for the skier. This FEA, shown in Figure 25 has acceptable stress values, however improvements could be made to limit the stress concentrated at the interface of the flange and the main body due to the square geometry. Complete FEA on top plate, fulcrum, and lever arm and stress-strain analysis can be found in Appendix C.
Table 4: Simulation Values for FEA Analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (m)</td>
<td>113.4 kg</td>
</tr>
<tr>
<td>Acceleration due to gravity (g)</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>Lean angle (α)</td>
<td>0°</td>
</tr>
</tbody>
</table>

Calculations for Tangential Force:

\[ F_t = 113.4 \text{ kg} \times 9.81 \text{ m/s}^2 \times \cos(0) \]
\[ F_t = 1,112.45 \text{ N} \]

Figure 25: Fulcrum Support - Force Applied to the Side Stress FEA

PROTOTYPE PRODUCTION

4.1 Acrylic Demonstration Prototype

4.1.1 Solidworks model

A model of the ski binding suspension system was designed using Solidworks computer automated design (CAD) software. All the parts were designed and put into an assembly to
assure appropriate sizing. Figure 26 shows the front of the design assembled and the rear of the design as an exploded view to see all of the components of design.

![Figure 26: CAD Model of Ski Binding Suspension System](image)

The top plate, bottom plates, lever arms, actuator, spring frame sides, and fulcrum supports were all able to be made from clear acrylic.

### 4.1.2 Laser Cutting

The parts that were made from clear acrylic were able to be laser cut. Laser cutting is a relatively simple manufacturing process. Three different thicknesses of acrylic were needed to make all the laser cut parts, including 1/4in, 3/16in, and 1/2in pieces. The Solidworks parts were converted into two dimensional drawings of the faces that were to be laser cut.

The top plate, lever arms, actuator, and fulcrum supports were 1/2in thick and therefore made from the 1/2in acrylic. The bottom plates were made from the 1/4in acrylic and the four spring frame sides were made from 3/16in acrylic.

These drawings were opened in AutoCAD and then edited to be compatible to the laser cutter software. The laser cutter that was used works as a printer driver, so the parts could be printed directly from AutoCAD to the laser cutter software.

### 4.1.3 Machining

The laser cutter is only able to cut on a single plane and to a maximum depth of 1/2in, therefore the holes for the pins that run through the front faces of the top plate and lever arm would need to be drilled. Also, the holes for the fulcrum supports for attaching to the bottom plates needed to be drilled.
Laser cutting the exact shape of both the lever arms and top plates causes portions of the part that require drilling to be cantilevered. Acrylic is not a relatively strong plastic and is quite brittle resulting in breaking on first drilling attempts.

To combat this problem new parts were laser cut without the removal of material that would result in a thin, cantilevered beam. With the middle section still intact, drilling through the acrylic was possible. After drilling, the material that needed to be removed was done using a vertical band saw and manual mini mill.

The pins that connect the top plate, lever arm, actuator, and spring system were made from 6061 Aluminum. A manual lathe was used to manufacture these pins, which included grooves for the external retention clips that were used to keep the pins in place in the system. The spring posts in the spring frame were also made from 6061 Aluminum and machined on a manual lathe.

4.1.4 Assembly

Once all parts were machined or laser cut, they were assembled with various fasteners, that were purchased as shown in Figure 27. These included shoulder bolts and jam nuts for the spring frame, cap head bolts to attach fulcrum supports to the bottom plates which were previously tapped for the bolts, external retention clips for the pins, and super glue to attach the spring frames to the bottom plates.

![Figure 27: Final Assembly of Physical Integration](image)

The shoulder bolts needed to be modified to allow for clearance of the lever arm as it moves when the system displaces. The threaded end needed to be trimmed to an appropriate length and the heads of the bolts needed to be grinded down a small amount to allow the lever arm to move without obstruction. Upon assembly, with the exception of the Goat Head Spring, a working demonstration model was created.
4.2 Spring Production

Different materials were selected based on desired mechanical properties the spring needed to achieve within the prototype design including AISI 1095 Carbon Spring Steel, Polytetrafluoroethylene (PTFE) also referred to as Teflon, and Ethylene-vinyl acetate (EVA). The forces required to initiate initial displacement and deformation were calculated to determine an appropriate spring material. See Appendix D for material selection based on calculations and spring dimensions. Material was selected based on the material properties (Elastic Modulus and yield stress) and the dimensions of the spring shown in Figure 28.

![Figure 28: Dimensioning of Goat Head Spring Labeled](image)

Calculations for required spring force at initial displacement:

\[
\varepsilon_{spring} = \frac{t}{2R_n}
\]

\[
\sigma_{spring} = \varepsilon_{spring} \times E \times 10^6
\]

\[
F_{spring} = \sigma_{spring} \times A
\]

Where:

- \( \varepsilon_{spring} \) = Spring strain (m/m)
- \( t \) = thickness (m)
- \( R_n \) = radius to neutral axis (m)
- \( A \) = cross-sectional area (m²)
\( \sigma_{\text{spring}} = \) Spring stress (MPa)
\( E = \) Elastic Modulus (GPa)
\( F_{\text{spring}} = \) Required spring force (N)
\( A = \) cross-sectional area \((m^2)\)

Calculations for required spring force at plastic deformation:

\[ F_{\text{deformation}} = YS \times A \times 10^6 \]

Where:

\( F_{\text{deformation}} = \) Force required for plastic deformation (N)
\( YS = \) Yield stress (MPa)

4.2.1 Metal Springs

Metal springs were made from AISI 1095 Carbon Spring Steel, an easily formed metal intended for mechanical spring applications using standard bending and heat treatment methods detailed in Appendix E and Appendix F respectively.

4.2.1.1 Bending

The springs were formed using a manual bending mechanism shown in Figure 29, following a 3 step process in which the spring was first bent around a cylindrical post with outer diameter of 0.0254m (1in), rotated and bent around a cylindrical post with outer diameter of 0.027m (0.5in), and rotated again and bent around a cylindrical post with outer diameter of 0.0254m (1in).

![Figure 29: 3-Step Configuration of Metal Goat Head Spring](image-url)
Two types of metal springs were produced with cross-sections of 1/16in X 1/16in and 1/8in X 1/8in shown in Figure 30. Using the spring force equations, the maximum applied force for the 1/16in X 1/16in and 1/8in X 1/8in was calculated to be equal to 1,247.48N (280.46lbs) and 4,989.93N (1,121.84lbs) respectively.

![Figure 30: Fabricated Metal Goat Head Springs](image)

4.2.1.2 Heat Treating

Once the springs were formed, they were hardened at 900°C, quenched in oil, and tempered at 650°C. This process is essential because as heat is increased, brittleness decreases, creating better properties for spring applications.

4.2.2 Plastic Demonstration Springs

Alternatively to the metal spring solution, two types of plastic springs were made using Teflon, a slippery vinyl polymer, and EVA, a flexible low-force plastic. Using the spring force equations, the required applied force for spring displacement of springs made from Teflon and EVA with dimensions of 1/16in X 1/16in was calculated to be 36.35N (8.17lbs) and 1.91N (0.43lbs) respectively shown in Appendix D. Based on the calculations, Teflon proved to be a suitable material for demonstrating the spring mechanism of the prototype, which would require little force from the user to displace the boot-binding system at either the toe or heel.

The Teflon springs were machined using Computer Numerical Control (CNC) machining methods on a mini mill. A Solidworks file was uploaded to Esprit, which was then generated code for machining. The EVA springs were fabricated from hot glue gun sticks containing an EVA and wax mixture. The glue sticks were melted and traced onto parchment paper following the shape of a Goat Head Spring. This particular method and material resulted in ineffective
springs. A more effective technique for future fabrication of EVA springs would be to inject EVA with no additives into a mold using an industrial hot glue gun by 3M Scotch Weld.

TESTING AND FINAL DESIGN

5.1 Testing Against the Axioms

Axiomatic design principles indicate that the design must be both collectively exhaustive and mutually exclusive (CEME) while maintaining the independence of the functional requirements and minimizing the information required to fulfil the functions. The decomposition matrix for this design shows there is coupling within the mechanism, meaning there are components that perform multiple functions. These aspects of the design do not abide by axiom 1 which is to maintain the independence of the functional requirements. For example, the fulcrums and pins perform multiple functions transferring vertical loads through the suspension system and limiting the movement in the yaw and roll directions. Despite these coupling situations, the reminder of the design abides by the axioms.

5.2 Spring Testing

The theory behind the Goat Head Spring is that it is a constant force spring within the elastic region of the material allowing the material to deform under a load and return to its original shape without any plastic deformation. Graph 2 shows the theoretical force vs. displacement graph of a constant force spring relative to ordinary and injury loads while skiing. For these springs to be successful for this application, the springs should exhibit a force displacement curve similar to the one shown below.

Graph 2: Goat Head Spring Theory
The metal heat treated springs were tested using an Instron machine per the testing procedures outlined in Appendix G for a 3-point bending test. The springs were displaced 1.5mm, 3.0mm, and 4.5mm, returning to the original position after each displacement. Two metal springs were tested. One with a width of 1/8in and the other with a width of 1/16in, both with the same heat treatment. After the testing, both springs had plastically deformed and did not return to their original shape after the testing.

The force vs. displacement graph testing results for the 1/16in spring is shown in Graph 3. After the 1.5mm displacement, the spring almost completely returned to its original shape. After both the 3mm and 4.5mm displacements, the spring was not able to return to its original shape and showed plastic deformation. For data on 1/8in and 1/16in springs, see Appendices H and I respectively.

Graph 3: 1/16in Spring Test Results

This graph does resemble the theoretical Goat Head Spring graph shown in Graph 2, however the heat treated springs did not return to their original shape. The horizontal lines in the test data are the spring plastically deforming, no longer able to ‘spring’ back as a spring should. The plastic EVA and Teflon springs were not tested, however the same test method can be applied to these springs to test them in the future.

5.3 Proof of Concept Prototype

The physical model of the suspension system mechanism proved to be successful and engage the springs when the heel and/or toe of the binding moved vertically. The components of the physical mechanism aligned and were able to transfer the loads from the binding through the
lever system and to the springs. However, the springs were not able to engage as a constant force spring. The Goat Head Spring made of Teflon showed plastic deformation prohibiting the top plate from springing back into the neutral horizontal position after the loads had been absorbed by the spring. With a working Goat Head Spring, the proof of concept prototype could be fully functional, with the constant force resistance in the springs when the plate displaces.

ITERATION

6.1. Modifications as a result of testing

During the manufacturing and testing processes of the demonstration model, some small iterations were made to the design and the process in which some of the part were manufactured. In the design, three changes were made. First, the base plate which attaches the entire suspension system to the ski, was split into two pieces and had a more product-realistic contour designed. This alteration reduced the weight of the demo model and would be a change that would be included on any future prototype or consumer model. Additionally, the bearings were excluded from the demo assembly. For the limited use required of the demo model, and the satisfaction of the aluminum pin and acrylic fulcrum contact, no bearings were used in the fulcrums for the rotation of the lever system. Bearings, or a similar substitute such as a bushing will most likely be used for a functioning prototype. Moreover, the cotter pins set to retain the fulcrum pin were replaced by external retention rings (E-rings). These E-rings were already being used in multiple locations elsewhere on the demo model, and had the same use as the cotter pins, however, may be slightly more difficult to remove and attach. The decision to use E-rings on this pin as well, was made to reduce the manufacturing time, as the grooves on the pins were a repeatable process and too reduce the types of hardware used on the model. The fewer the types of hardware, the easier and cheaper it is for replacement parts. This alteration would have benefit on future prototypes.

6.2. Modifications for skiable prototype

With the alteration of some of the materials in the demo model to more realistic materials, additional modifications will need to be made for the upgrade into a skiable prototype. To inhibit the accumulation of snow and other interfering particulates, the entire mechanism will need to be
encased in an enclosure. This enclosure will need to be formed to reduce any drag as the binding has the possibility of being used in powdery and icy snow conditions. To further improve the adjustability of a skiable model, the replacement of the fulcrum adjustment with a screw-like adjustment system will allow for more variance and fine tuning of the spring system. Furthermore, pocketing and other forms of weight reduction will need to be factored in for a skiable prototype. Finite Element Analysis of the demo model can assist in this by highlighting the areas of excessive support where material can be removed. Lastly, the model will need to have a smaller profile to fit a wider variety of skis. This will allow for more proper skiing technique as well as weight reduction. Changes such as centering a single fulcrum on the lever system will greatly reduce the required width of the lever located at the fulcrum location.

DISCUSSION

7.1 Evaluation of the design and design process

The axiomatic design process is beneficial as it provides a rigorous structure to aid in the development of a design. The structure required the designers to continuously reflect on how each individual functional requirement and design parameter would fulfill the customer’s needs in the final design. This framework for design did not allow for any generic brainstorming about the customer’s needs as a whole. Each individual level of the decomposition had some freedom for brainstorming as the design parameters were selected, but the overall process prohibited thinking about the end product as a complete system.

The ski binding suspension system design will fulfill the customer’s needs to protect the ACL from injuries while skiing while avoiding inadvertent release. The ability to replace the springs and adjust the lever system allow the device to be used by all skiers. The constant force springs allow the user to ski normally and engage only during a potentially injurious situation. With additional research on the constant force Goat Head Springs, the design can be fully functional and further developed into a skiable prototype.

7.2 Constraints

Numerous constraints, including consumer, environmental, ethical, health and safety, and manufacturability were considered during the design process of the Suspension System. The
level of satisfaction of the design can be determined based on the number of constraints that were fulfilled as shown in Table 5.

Table 5: Satisfaction of Design Constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Final Design</th>
<th>Successful? (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alpine Downhill Race Standards</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width of plate must be less than the max standard: Downhill - 95 mm</td>
<td>95 mm</td>
<td>Yes</td>
</tr>
<tr>
<td>Standing Height (ski/plate/binding) must be less than 50 mm</td>
<td>50 mm</td>
<td>Yes</td>
</tr>
<tr>
<td>Boot height (from sole of boot to top of foot bed) must be less than 43 mm</td>
<td>0mm</td>
<td>Yes</td>
</tr>
<tr>
<td>Boot Interface - ISO 5355 Alpine ski boots-Requirements and test methods</td>
<td>ISO 5355 Alpine ski boot mounting holes on top and bottom plate</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Ski Binding Suspension System Specifications</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Withstand Vertical Critical Load ( (F_{spring} ) of 2.25*Body Weight</td>
<td>AISI 1095 Carbon Spring Steel (1,247.48N), Teflon (36.35N), EVA (1.91N)</td>
<td>No</td>
</tr>
<tr>
<td>Deflection at Injurious Loads - replicate the constant spring force vs. displacement curve</td>
<td>AISI 1095 Carbon Spring Steel, Teflon, EVA</td>
<td>No</td>
</tr>
<tr>
<td>Heel Height</td>
<td>± 5mm</td>
<td>Yes</td>
</tr>
<tr>
<td>Toe Height</td>
<td>± 5mm</td>
<td>Yes</td>
</tr>
<tr>
<td>System Mass</td>
<td>3,134.05g</td>
<td>No</td>
</tr>
<tr>
<td>Cycles to Failure - over thousands of cycles</td>
<td>Not tested</td>
<td>No</td>
</tr>
<tr>
<td><strong>Environmental Conditions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mountain terrain conditions (no snow or ice jams)</td>
<td>No covering</td>
<td>No</td>
</tr>
<tr>
<td>Environmental Temperatures</td>
<td>Depends on material of spring</td>
<td>Maybe</td>
</tr>
</tbody>
</table>
7.3 Impact on the user and industry

By reduction of ACL tears caused by skiing, the ski industry does not lose its customers due to rehabilitation of the injury. The ACL reconstructive surgery is expensive with a long recovery process requiring lifestyle changes. With this mechanism, the customers can continue their lifestyle of skiing with minimal concerns of the potential for ACL injury. This allows the sport to be more enjoyable for the user and the ski industry is able to benefit from their continued participation.

7.4 Deficiencies in the prior art that this invention improved upon

In prior ski binding systems meant to reduce ACL injuries, there were deficiencies that this design improved upon. In some of the prior art, mainly commercial products such as the KneeBinding, Reactor 12 by Line Skis and the Tyrolia Diagonal Toe and Heel Binding, the systems are focused on different release mechanisms. These release mechanisms may be effective at saving the ACL from being torn, however they cause the boot to be released from the binding and the ski which may cause other injuries. This deficiency of releasing the boot from the binding is improved upon by absorbing the injurious loads and allowing the skier to recover. Absorbing the injurious loads not only saves the ACL from injury but also saves the skier from an inadvertent release, preventing these other types of injuries.

In other ski binding systems to protect the ACL from injury, especially from past MQP’s the systems included absorption systems, however the designs do not have a constant force system. By using a pre-loaded linear spring, the system is unable to displace under a constant load, therefore there is less displacement of the spring before injurious loads are reached.

Other ski binding systems meant to protect from tibial plateau and back injuries such as the Dodge Ski Boot change the natural frequency that is applied to the back and knees. In this design any boot can be used in the system to change the natural frequency of the system with the constant force spring.

7.5 Commercial uses

With further progression of the Vertical Suspension System, a consumer product could be developed for use in recreational and competitive ski markets. Further progression of the product
to include suspension systems in the yaw and roll directions would also benefit a possible consumer product, as this would assist in preventing other injury mechanisms. Further modification of the system could extend from alpine skiing into other ski markets such as ski jumping. In addition, the system can be scaled and/or modified for use in other sports that have the possibility of large vertical injury loads. Other sports can include those like snowboarding and skateboarding where rigidity is required under normal conditions.

CONCLUSIONS

- Major Accomplishments
  - Designed a ski binding suspension system to absorb vertical loads using axiomatic design
  - Manufactured constant force springs of different materials using different manufacturing processes
  - Tested constant force springs on an Instron to check mechanical properties of springs and force vs. displacement curves
  - Manufactured a demonstration model of ski binding suspension system

- Critical Assessment of Effectiveness of Design Method
  - Used multiple iterations of the design decomposition to limit changes in the physical model
  - Multiple areas of the design were coupled due to the limited space available between the ski and binding, requiring a component to fulfill more than one functional requirement
  - Adjustment mechanisms, being different from the binding, do not minimize the information required for the entire system

- Concluding Issues Remaining
  - Material and dimension selection for constant force springs
  - Development of skiable prototype
  - Size of prototype to accommodate different sizes of skis and bindings
  - Development of suspension system to absorb pitch and yaw moments
REFERENCES


Spinger, J 2016, Knee binding demo - avoid ACL injury, video recording, YouTube, viewed 30 September 2018, Available from: https://www.youtube.com/watch?v=zrLZWXwAgYc


APPENDIX A: Axiomatic Design Decomposition Iterations

This initial axiomatic decomposition shows the start of understanding the relationship between the customer needs and functional requirements. The design parameters were kept general to not complicate the solution in the early stages. This design focused on transmitting control loads from the skier, through the mechanism, to the snow and absorbing loads in injurious conditions. It was meant to absorb loads down at the heel, up at the toe, and laterally at the heel, rotating about the toe.

---

<table>
<thead>
<tr>
<th>#</th>
<th>FR Functional Requirements</th>
<th>DP Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transmit Control Loads</td>
<td>Plate to transmit control loads</td>
</tr>
<tr>
<td>1.1</td>
<td>Transmit loads from ski to plate</td>
<td>System to attach plate to ski</td>
</tr>
<tr>
<td>1.1.1</td>
<td>Allow ski to flex under the plate</td>
<td>Connection to allow ski to flex naturally</td>
</tr>
<tr>
<td>1.2</td>
<td>Transmit loads within plate</td>
<td>System to transfer loads within the plate</td>
</tr>
<tr>
<td>1.3</td>
<td>Transmit loads from plate to binding</td>
<td>System to attach binding to plate</td>
</tr>
<tr>
<td>2</td>
<td>Absorb injury loads</td>
<td>System to absorb injury loads</td>
</tr>
<tr>
<td>2.1</td>
<td>Absorb CVIR loads</td>
<td>System to create horizontal displacement at the heel</td>
</tr>
<tr>
<td>2.2</td>
<td>Absorb BIAD loads</td>
<td>System to create vertical displacement</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Create positive vertical displacement at the toe (up)</td>
<td>Mechanism to push toe up</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Create negative vertical displacement at the heel (down)</td>
<td>Mechanism to pull heel down</td>
</tr>
<tr>
<td>2.2.3</td>
<td>Adjust absorption for different skiers</td>
<td>Mechanism to adjust absorption of loads</td>
</tr>
<tr>
<td>2.3</td>
<td>Absorb tibial plateau injury loads</td>
<td>System/material to absorb high energy frequencies</td>
</tr>
</tbody>
</table>

Appendix Figure A1: Initial Axiomatic Decomposition

---

Appendix Figure A2: Midpoint Axiomatic Decomposition
APPENDIX B: Alpine Equipment Regulations

Alpine Equipment Regulations 2017-18

U19 and Older Equipment

<table>
<thead>
<tr>
<th>Description</th>
<th>Event</th>
<th>FIS</th>
<th>National</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ski Length</td>
<td>DH Ladies</td>
<td>210 cm min.**</td>
<td>183 cm min.</td>
</tr>
<tr>
<td>Ski length measurement tolerance +/- 1 cm</td>
<td>DH Men</td>
<td>218 cm min.**</td>
<td>183 cm min.</td>
</tr>
<tr>
<td>** -5 cm tolerance for FIS/ENL competition</td>
<td>SG Ladies</td>
<td>205 cm min.**</td>
<td>183 cm min.</td>
</tr>
<tr>
<td></td>
<td>SG Men</td>
<td>210 cm min.**</td>
<td>183 cm min.</td>
</tr>
<tr>
<td></td>
<td>GS Ladies</td>
<td>188 cm min.**</td>
<td>No rule</td>
</tr>
<tr>
<td></td>
<td>GS Men</td>
<td>193 cm min.**</td>
<td>No rule</td>
</tr>
<tr>
<td></td>
<td>SL Ladies</td>
<td>155 cm min.</td>
<td>130 cm min.</td>
</tr>
<tr>
<td></td>
<td>SL Men</td>
<td>165 cm min.*</td>
<td>130 cm min.</td>
</tr>
<tr>
<td>Radius</td>
<td>DH Ladies &amp; Men</td>
<td>50 m min.</td>
<td>30 m min.</td>
</tr>
<tr>
<td></td>
<td>SG Ladies</td>
<td>40 m min.</td>
<td>30 m min.</td>
</tr>
<tr>
<td></td>
<td>SG Men</td>
<td>45 m min.</td>
<td>30 m min.</td>
</tr>
<tr>
<td></td>
<td>GS Ladies &amp; Men</td>
<td>30 m min.</td>
<td>17 m min.</td>
</tr>
<tr>
<td></td>
<td>SL Ladies &amp; Men</td>
<td>No rule</td>
<td>No rule</td>
</tr>
<tr>
<td>Profile width in front of Binding</td>
<td>DH Ladies &amp; Men</td>
<td>95 mm max.</td>
<td>No rule</td>
</tr>
<tr>
<td></td>
<td>SG Ladies &amp; Men</td>
<td>95 mm max.</td>
<td>No rule</td>
</tr>
<tr>
<td></td>
<td>GS Ladies &amp; Men</td>
<td>103 mm max.</td>
<td>No rule</td>
</tr>
<tr>
<td></td>
<td>SL Ladies &amp; Men</td>
<td>No rule</td>
<td>No rule</td>
</tr>
<tr>
<td>Profile width under Binding</td>
<td>DH Ladies &amp; Men</td>
<td>65 mm max.</td>
<td>No rule</td>
</tr>
<tr>
<td></td>
<td>SG Ladies &amp; Men</td>
<td>65 mm max.</td>
<td>No rule</td>
</tr>
<tr>
<td></td>
<td>GS Ladies &amp; Men</td>
<td>65 mm max.</td>
<td>No rule</td>
</tr>
<tr>
<td></td>
<td>SL Ladies &amp; Men</td>
<td>63 mm min.</td>
<td>No rule</td>
</tr>
<tr>
<td>Standing Height (ski/plate/binding)</td>
<td>all events</td>
<td>50 mm max.</td>
<td>50 mm max.</td>
</tr>
<tr>
<td>Boot Height (from sole to top of foot bed)</td>
<td>all events</td>
<td>43 mm max.</td>
<td>43 mm max.</td>
</tr>
</tbody>
</table>

NOTE: The jury is empowered to prevent an athlete from starting if equipment is deemed inappropriate for the event being contested.
APPENDIX C: Finite Element Analysis

Appendix Figure C3: Top Plate – Stress FEA

Appendix Figure C4: Top Plate - Strain FEA
Appendix Figure C5: Top Plate - Displacement FEA

Appendix Figure C6: Lever Arm - Stress FEA

Appendix Figure C7: Lever Arm - Strain FEA
Appendix Figure C8: Lever Arm - Displacement FEA

Appendix Figure C9: Fulcrum Support - Force Applied Down, Stress FEA

Appendix Figure C10: Fulcrum Support - Force Applied Down, Strain FEA
Appendix Figure C11: Fulcrum Support - Force Applied Down, Displacement FEA

Appendix Figure C12: Fulcrum Support - Force Applied Up, Stress FEA

Appendix Figure C13: Fulcrum Support - Force Applied Up, Strain FEA
Appendix Figure C14: Fulcrum Support - Force Applied Up, Displacement FEA

Appendix Figure C15: Fulcrum Support - Force Applied to Side, Stress FEA

Appendix Figure C16: Fulcrum Support - Force Applied to Side, Strain FEA
Appendix Figure C17: Fulcrum Support - Force Applied to Side, Displacement FEA
APPENDIX D: Spring Material Calculations

Table 6: 1/16in X 1/16in Spring Material Calculations

<table>
<thead>
<tr>
<th>VALUES</th>
<th>inch</th>
<th>meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>2</td>
<td>0.050800102</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.0625</td>
<td>0.001587503</td>
</tr>
<tr>
<td>Radius to Neutral Axis</td>
<td>0.625</td>
<td>0.015875032</td>
</tr>
<tr>
<td>Thickness / 2</td>
<td>0.03125</td>
<td>0.000793752</td>
</tr>
<tr>
<td>Cross Sectional Area</td>
<td>0.125</td>
<td>8.06453E-05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Spring Stress (MPa)</th>
<th>Required Force for Spring (N)</th>
<th>Required Force for Plastic Deformation (N)</th>
<th>Required Force for Plastic Deformation (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Irons</td>
<td>8625</td>
<td>695565.9073</td>
<td>156377.2274</td>
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<td>10375</td>
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<td>188105.9401</td>
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<td>180853.6629</td>
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<tr>
<td>Non-ferrous</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Alloys</td>
<td>3750</td>
<td>302419.9597</td>
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<td>687.5</td>
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<td>Butyl Rubber</td>
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<td>Spring Stress (MPa)</td>
<td>Required Force for Spring (N)</td>
<td>Required Force for Plastic Deformation (N)</td>
<td>Required Force for Plastic Deformation (lbs)</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------</td>
<td>--------------------------------</td>
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**Table 7: 1/8in X 1/8in Spring Material Calculations**

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<tr>
<td>Thickness</td>
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<td>Material Type</td>
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<td>Density (g/cm³)</td>
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APPENDIX E: Metal Spring Protocol

Metal Spring Heat Treatment Protocol

Materials:
- 1095 Steel Metal Goats Head Spring
- Thermo Scientific Thermolyne F48015-60 Muddle Furnace
- Oven mitts
- Hougo-Quench G Quenching Oil
- Tongs
- 2 Brick Supports

Protocol:
1. Place 2 brick supports inside the furnace with enough space between them for the tongs to access.
2. Lay the spring(s) flat on the two supports.
3. Preheat the furnace to 900°C and then let the springs cook for 1 hour.
4. Use the tongs to remove the spring.
5. Quench in oil (do not release grip from spring).
6. Turn the furnace off.
7. Let the spring cool for 24 hours.
8. After cooling, reheat furnace to 650°C and cook springs for 1 hour.
9. Remove springs from furnace and let cool to room temperature.
10. Turn furnace off.
APPENDIX F: Spring Heat Treatment Protocol

Metal Goat Head Spring Protocol

Materials:
- Spring Steel Machine Key Stock
  - ⅛” x ⅛” stock from McMaster-Carr: Part # 98535A130
  - 1/16” x 1/16” stock from McMaster-Carr: Part # 98535A120
- Bending Machine
- Inner post (½ inch)
- Outer post (1 inch)
- Contact pin
- Dremel

Procedure:
1. Place inner post in the center of the bending machine and the outer post around the inner post.
2. Lay the stock between the outer post and the contact pin so that the end of the stock is well gripped.
3. Begin to rotate the handle, slowly bending the stock to ¾ of the circumference of the outer post.
4. Remove the stock and the outer post. Re-adjust the stock and contact pin to bend about the inner post.
5. Rotate the handle, slowly bending the stock to ½ of the circumference of the inner post.
6. Remove the stock and place the outer post around the inner post. Re-adjust the stock and contact pin to bend about the outer post.
7. Rotate the handle, slowly bending the stock to ¾ of the circumference of the outer post.
8. Remove stock and cut off extra stock with the Dremel.

Appendix Figure F18: 3-Step Bending Configuration of Goat Head Spring
APPENDIX G: Force vs Displacement Instron Test Protocol

Materials:
- Instron
- Software
- Compression 3-point loading test method
- 2 1” cylinder supports
- V-block
- Text fixture
- Goat Head Spring
- Teflon tape
- Engineering graph paper

Protocol:
1. Open compression test method in the Software.
2. Load test fixture into load cell on the Instron.
3. Take a “before” picture of the Goat Head Spring on engineering graph paper.
4. Wrap the cylinder supports with Teflon tape and then place each support on the v-block on the Instron.
5. Set the 2 outer diameters of the Goat Head Spring on top of the cylinder supports.
6. Jog the load cell down until the cylinder on the fixture slightly contacts the spring without displacing it.
7. Zero displacement and force.
8. Run the test method.
9. Wait for test to finish.
10. Jog the load cell up away from the spring and remove spring.
11. Take an “after” picture of the Goat Head Spring on engineering graph paper.
12. Export and save test data to a csv. file.
Appendix Figure G 20: Before and After of Goat Head Spring due to Compression Test
APPENDIX H: Data from 1/8in Spring Force vs Displacement Test Results

Graph 4: 1/8in Metal Goat Head Spring Force vs. Displacement Test Results – 1.5mm

Graph 5: 1/8in Metal Goat Head Spring Force vs. Displacement Test Results - 3.0mm
Graph 6: 1/8in Metal Goat Head Spring Force vs. Displacement Test Results - 4.5mm
APPENDIX I: Data from 1/16in Spring Force vs Displacement Test Results

Graph 7: 1/16in Metal Goat Head Spring Force vs. Displacement Test Results - 1.5, 3, 4.5mm